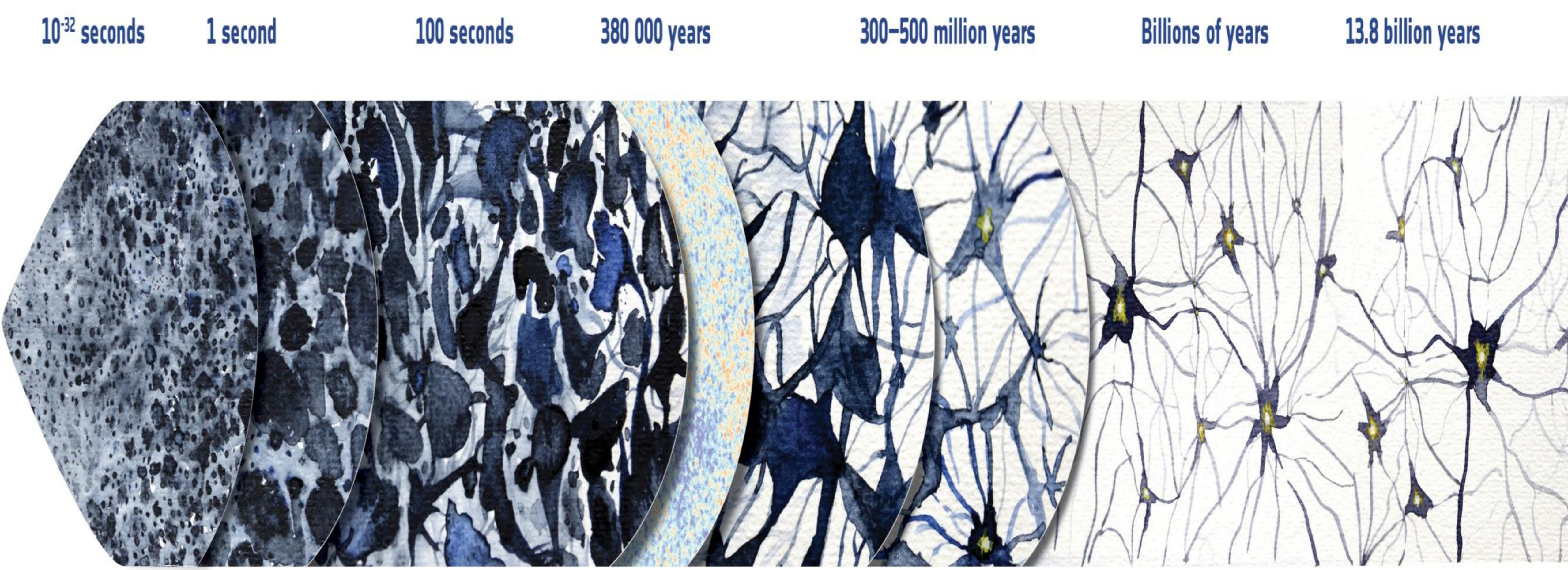


Ch.8 Cosmology

- Young Ju
- Physics Seminar II
- Book : Astroparticle Physics, Claus Grupen

www.esa.int/ESA_Multimedia/Search?SearchText=cosmic+history&result_type=images

Aim

- This chapter contains brief review of cosmology
- The detailed explanation of each concept is handled in the following other chapter

Cosmology model

- Standard cosmology model = Hot big bang model

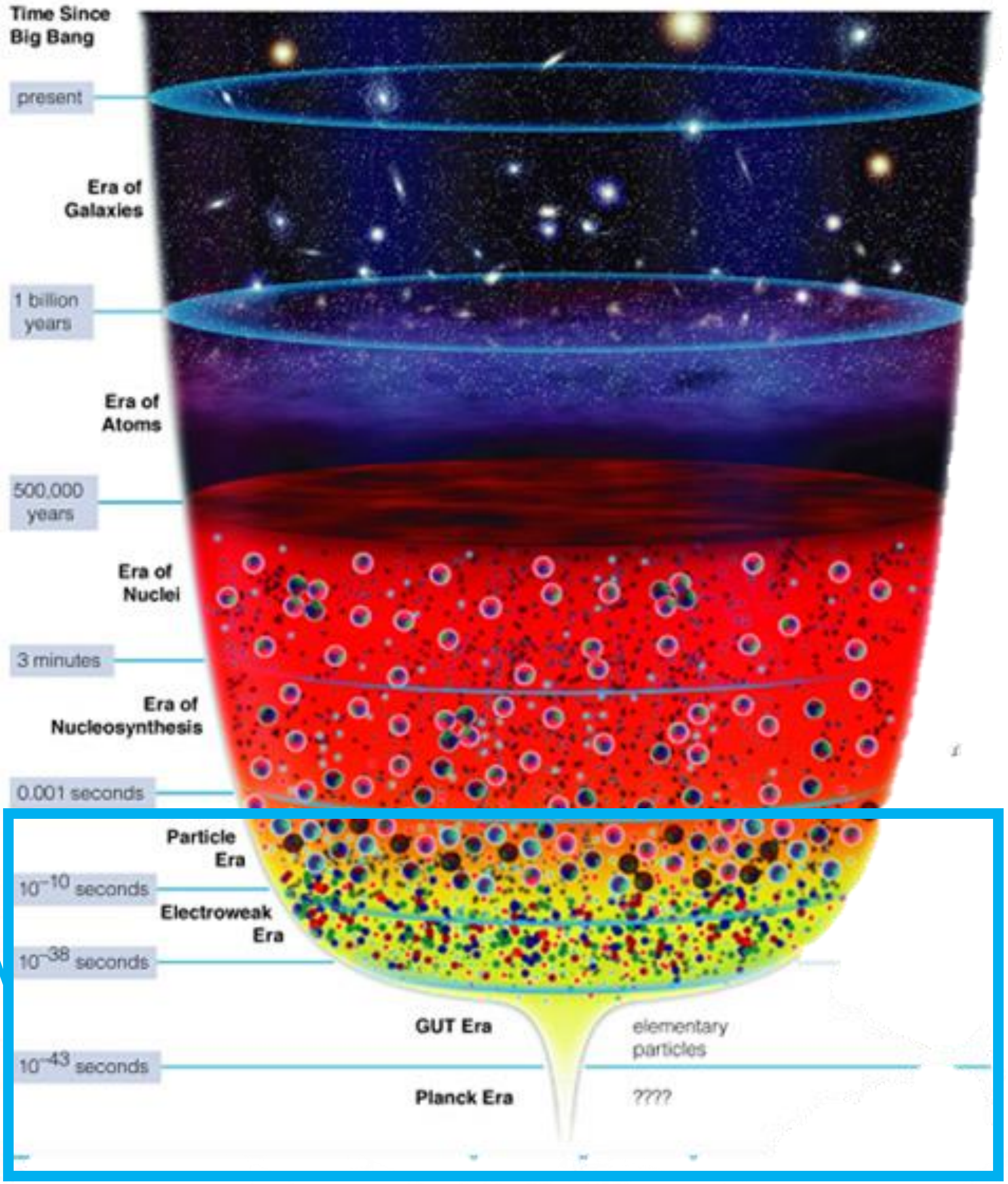
- Why do we agree this cosmology model?
  : there are 10 observation evidences for modern cosmology

1. SNIa data
2. CMB
3. LSS
4. light element abundance
5. Age
6. matter content
7. matter vs antimatter
8. the darkness of sky
9. existence of universe
10. existence of observer

(ref : 자연의 전망, 우주. 황재찬. 2020)

Cosmic history

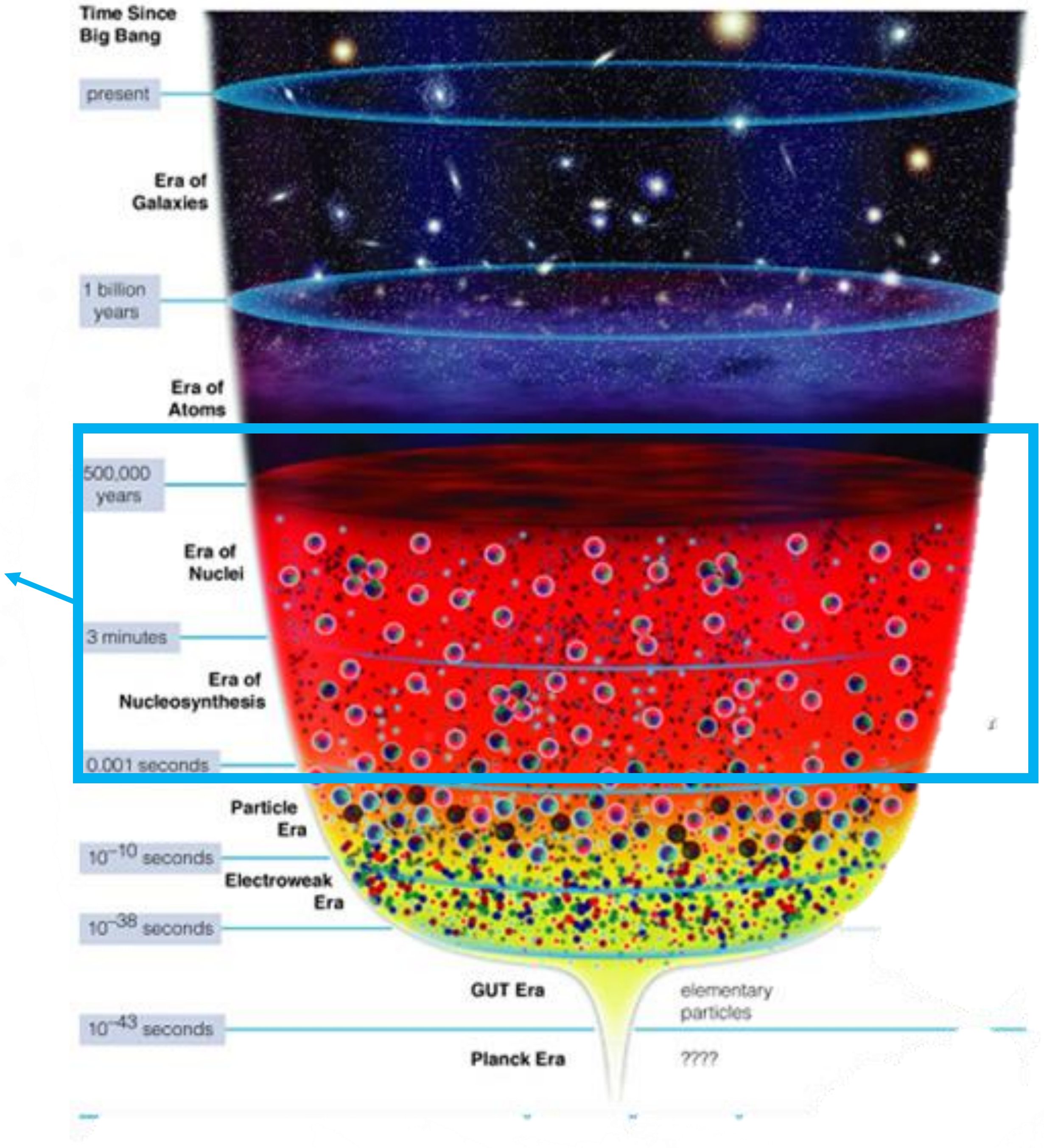
- 10^{-43} s : meaningful time
- 10^{-38} s : gravity & 3 fundamental forces
- $10^{-38} \sim 10^{-36}$ s : Inflation
- 10^{16} GeV : divided into strong & electroweak
- 100 GeV : electroweak divided into electromagnetic & weak
- 10^{-6} s : hot soup of quarks, leptons, photons, and other particles
- 1 GeV : annihilation of matter and antimatter



https://web.njit.edu/~gary/202/Lecture26.html

Cosmic history

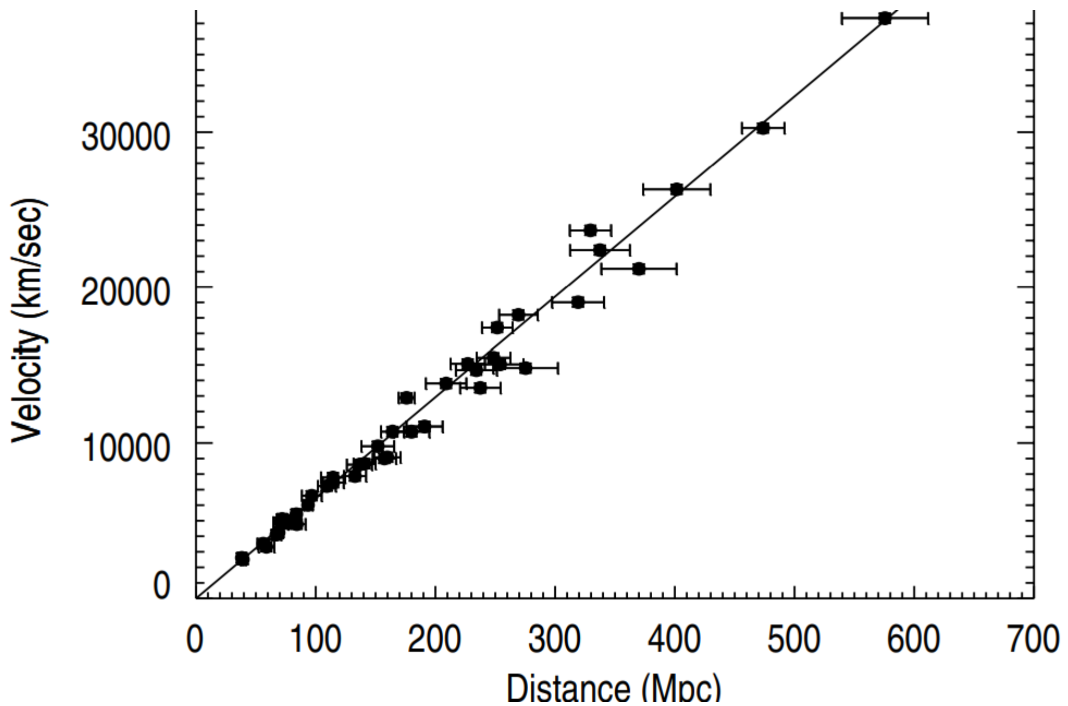
- 3 min : proton & neutron form deuteron
- Few minute : form helium and light elements : **BBN** (Big Bang Nucleosynthesis)
- 380,000 year : transparent to photon : CMB



https://web.njit.edu/~gary/202/Lecture26.html

Hubble expansion

- Hubble measured recession velocity and distance relation by using Cepheid variables
- Nowadays more distant region, SNIa data are used
- $\boldsymbol{v = H_o r}$



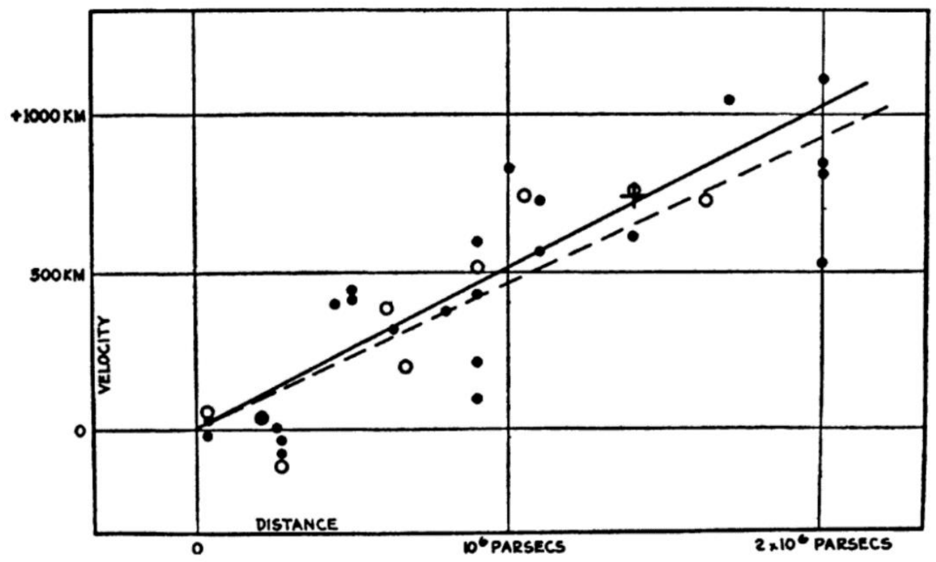
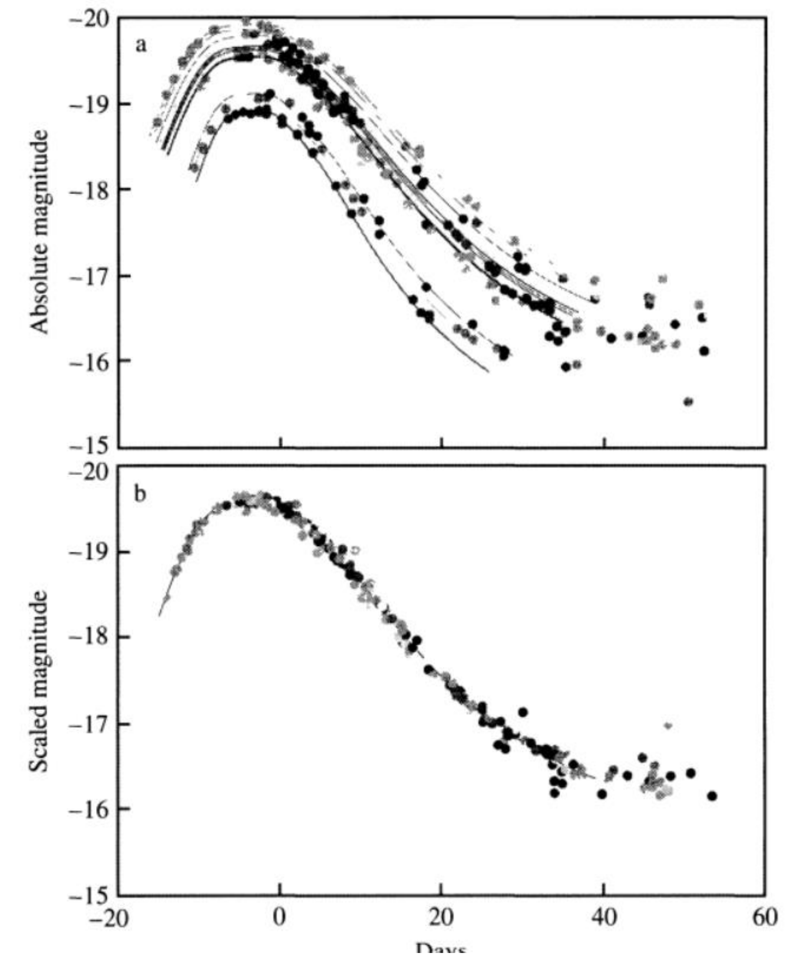


FIGURE 27.7 Hubble's 1936 velocity–distance relation. The two lines use different corrections for the Sun's motion. (Note: The vertical units should be km s^{-1}.) (Figure from Hubble, *Realm of the Nebulae*, Yale University Press, New Haven, CT, ©1936.)

Hubble expansion

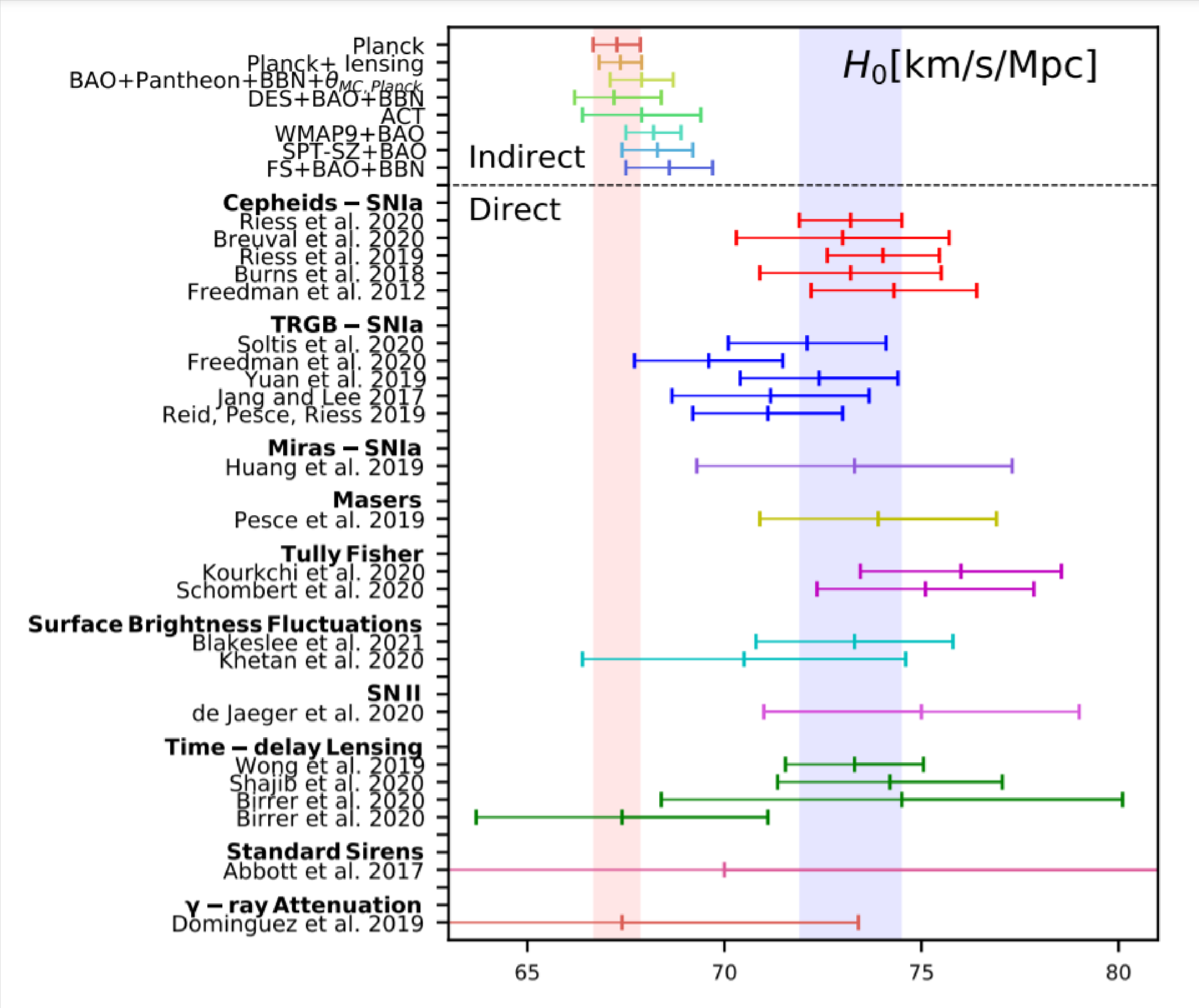
- The mechanism of SNIa is universal
- Even if we only measure apparent magnitude, we can estimate absolute magnitude
- But… there are lots of parameters to fit data



Hubble constant, H_0

- up-to-data Hubble constant

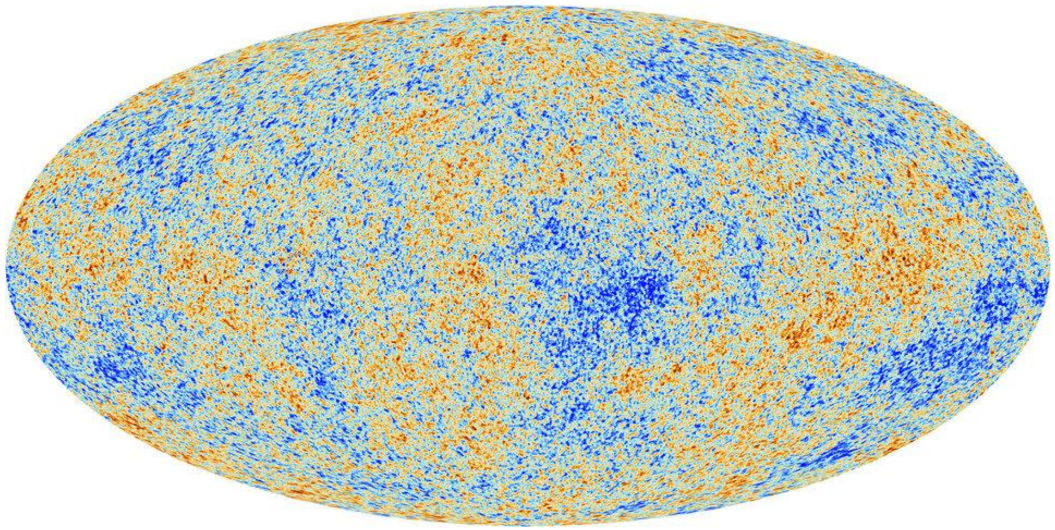
Ref: Di Valentino, 2021



Isotropy and homogeneity

- Cosmological principle : first assumption, but now it is proved by observation

- What is Isotropy and homogeneity?



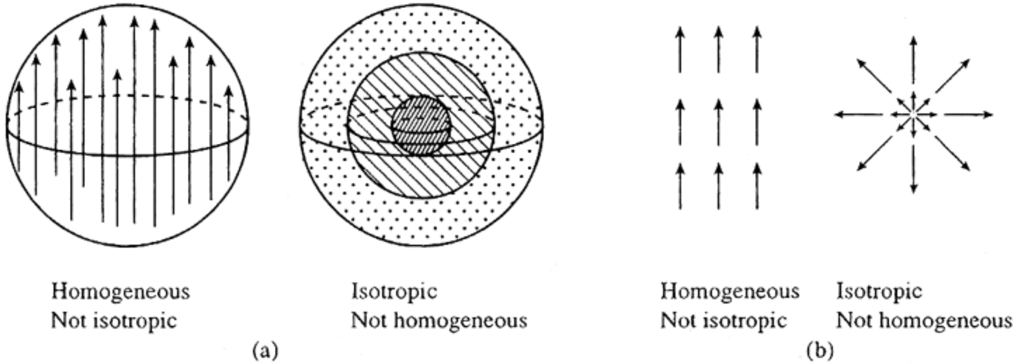


Figure 1.5 Illustrations of how homogeneity and isotropy are not equivalent in (a) three dimensions and (b) two dimensions. In the first example of each, a unique direction is picked out but translation invariance is maintained. In the second example of each, all directions are the same (rotation invariance) but a radial gradient exists.

Friedmann equation : with Newtonian gravity

- Consider spherical volume with many galaxies $$M = \frac{4}{3}\pi R^3 \varrho$$
- Total E : $$E = \frac{1}{2} m \dot{R}^2 - \frac{4\pi}{3} G m R^2 \varrho = \frac{1}{2} m R^2 \left(\frac{\dot{R}^2}{R^2} - \frac{8\pi}{3} G \varrho \right) \qquad k = \frac{-2E}{m} = R^2 \left(\frac{8\pi}{3} G \varrho - \frac{\dot{R}^2}{R^2} \right)$$
- 1st Friedmann equation $$\frac{\dot{R}^2}{R^2} + \frac{k}{R^2} = \frac{8\pi}{3} G \varrho$$
- 2nd Friedmann equation $$\frac{\ddot{R}}{R} = -\frac{4\pi G}{3}(\varrho + 3P)$$ (derivative of 1st eq.)

Friedmann equation : with thermodynamics

- Consider 1st law of thermodynamics

$$\mathrm{d}U = T\,\mathrm{d}S - P\,\mathrm{d}V$$

- And imagine that the sphere adiabatically expand or contract

$$\frac{\mathrm{d}U}{\mathrm{d}t} + P\frac{\mathrm{d}V}{\mathrm{d}t} = 0$$

- 3rd Friedmann equation

$$\dot{\varrho} + \frac{3\dot{R}}{R}(\varrho + P) = 0$$

Friedmann equation : with Einstein equation

- Metric tensor in GR $g_{\mu\nu}$

- Robertson-Walker metric $$\mathrm{d}s^2 = \mathrm{d}t^2 - R^2(t)\left[\frac{\mathrm{d}r^2}{1-kr^2} + r^2\left(\mathrm{d}\theta^2 + \sin^2\theta\,\mathrm{d}\phi^2\right)\right]$$

- Einstein field equation :
  The relationship between spacetime geometry and state of matter :
  $$\underbrace{\mathcal{R}_{\mu\nu} - \frac{1}{2}\mathcal{R}g_{\mu\nu}} = \underbrace{8\pi G T_{\mu\nu}} + \Lambda g_{\mu\nu}$$

Friedmann equation : with Einstein equation

- Friedmann equation

  Curvature, density, vacuum energu

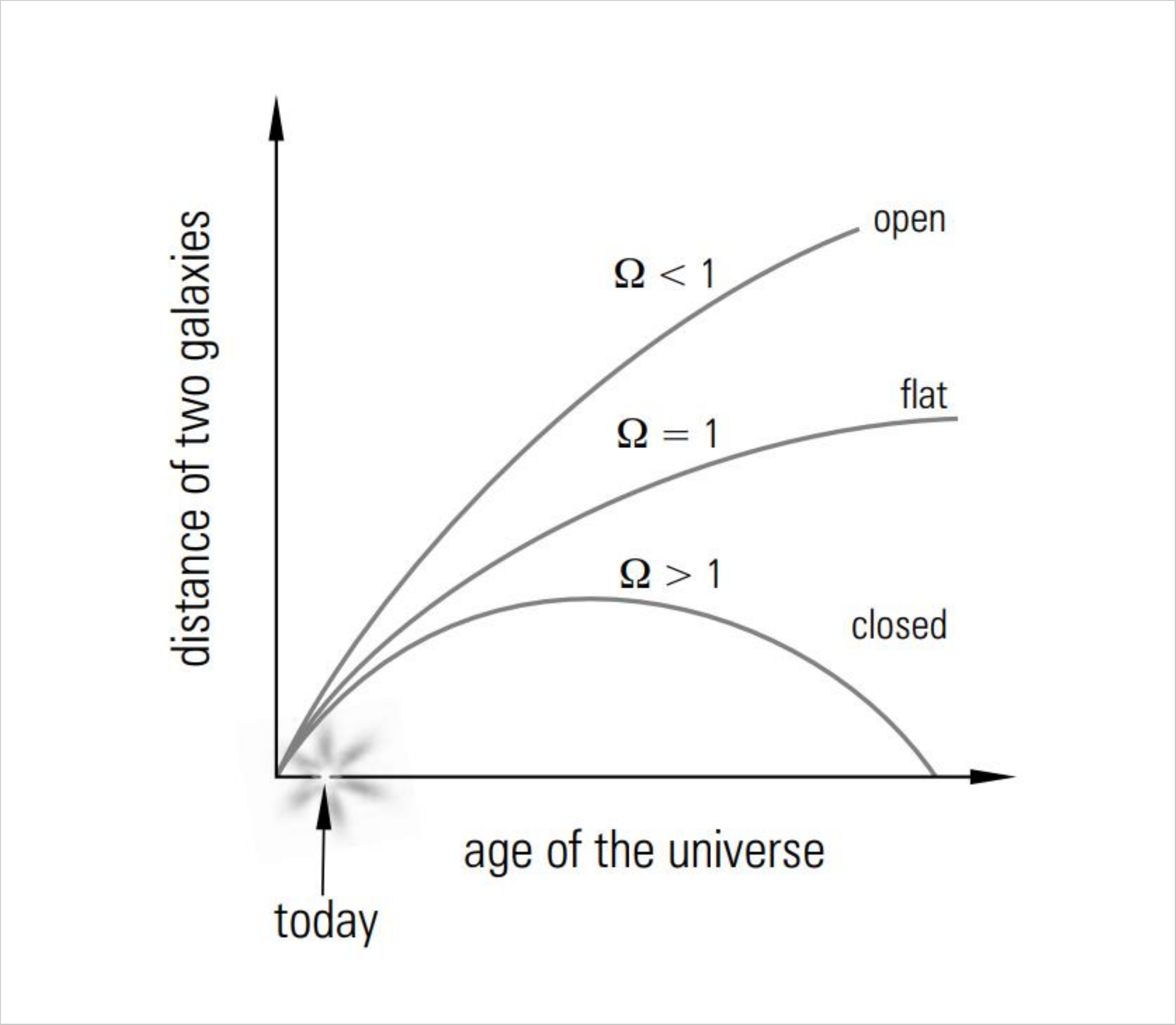
$$\frac{\dot{R}^2}{R^2} + \frac{k}{R^2} = \frac{8\pi}{3} G \varrho + \frac{\Lambda}{3} \qquad \frac{\ddot{R}}{R} = -\frac{4\pi G}{3}(\varrho + 3P) + \frac{\Lambda}{3} \qquad \dot{\varrho} + \frac{3\dot{R}}{R}(\varrho + P) = 0$$

What do we know from Friedmann eq. ?

- We can know about expansion of the universe
- Critical density : $\varrho_c = \dfrac{3H^2}{8\pi G}$

  (Curvature is zero)
- Curvature with density parameter

$$k = R^2(\Omega - 1)H^2$$



The expansion of the universe

Expectation :
Sometime expansion rate of the universe decreases due to matter

The SNIa data result :
our universe is accelerated

How do we figure it out?

Distance in cosmology

1. Comoving distance : measure the distance by using light

2. Proper distance : measure the distance at the same time

3. Luminosity distance : using conservation of the number of photon

$$d_l = \sqrt{\frac{L}{4\pi F}}$$

4. Angular diameter distance : consider that object has certain angular size

$$d_A = \frac{D}{\delta\theta}$$

The expansion of the universe

- Previously, we define RW metric.
- Now, we can derive Luminosity distance

$$d_L(z) = \frac{1+z}{H_0} \int_0^z \left[\Omega_{\Lambda,0} + (1+z')^3 \Omega_{m,0} + (1+z')^2 (1-\Omega_0) \right]^{-1/2} dz'$$

- Second, we can measure redshift and apparent magnitude of SNIa

$$m = 5 \log_{10} \left(\frac{d_L}{1\,\mathrm{Mpc}} \right) + 25 + M$$

- As varying the cosmological model, we fit data to model

The expansion of the universe

- Deceleration parameter, q